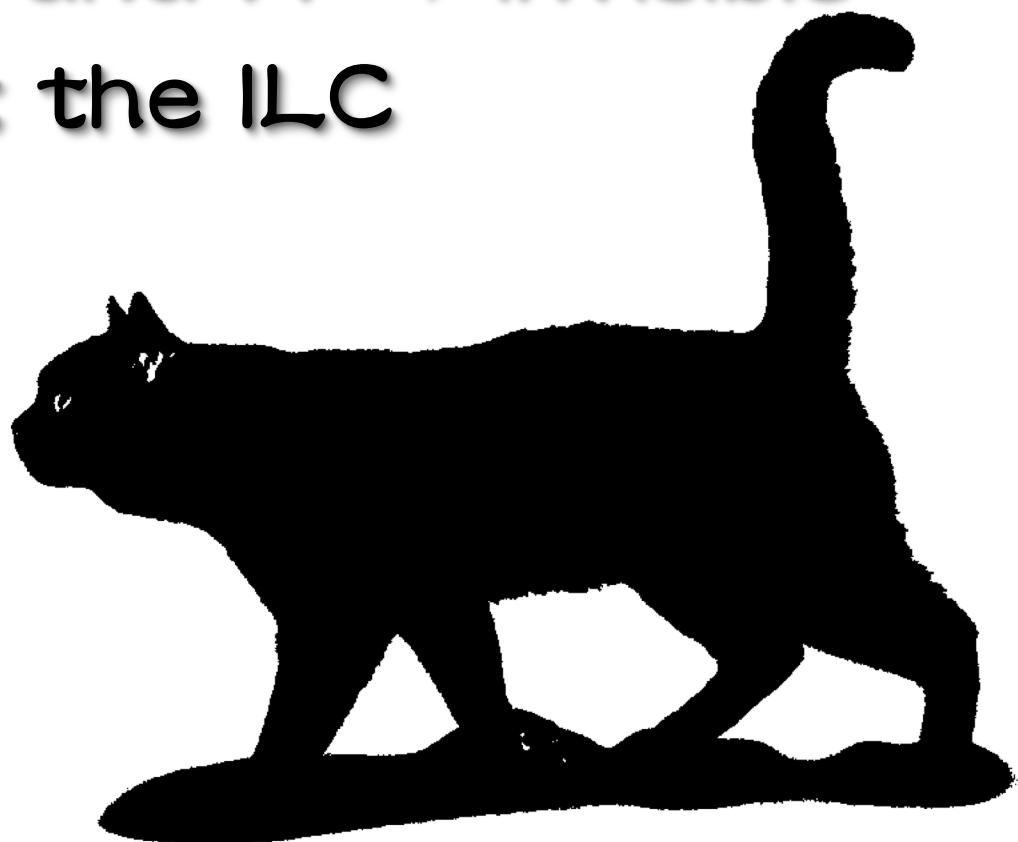
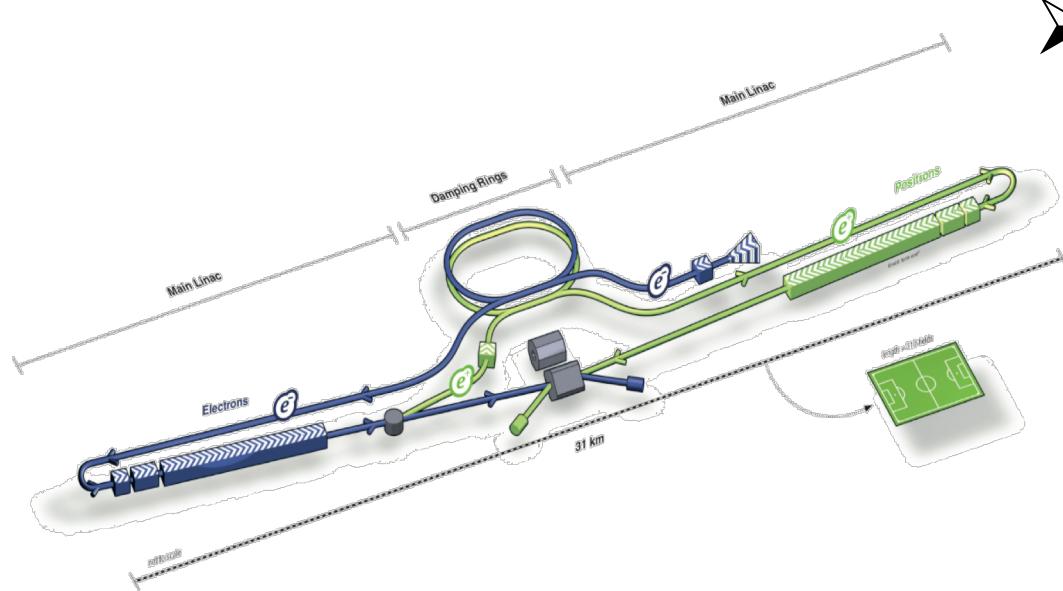


Studies of Higgs mass and $H \rightarrow$ invisible at the ILC



Shun Watanuki (IJCLab)

International Linear Collider (ILC)



➤ ILC

- e^+e^- collision with $E_{CMS}=250, 350, 500\text{GeV}$
- Upgrade up to 1 TeV
- Polarized beam
→ NP enhancement

➤ Expected features

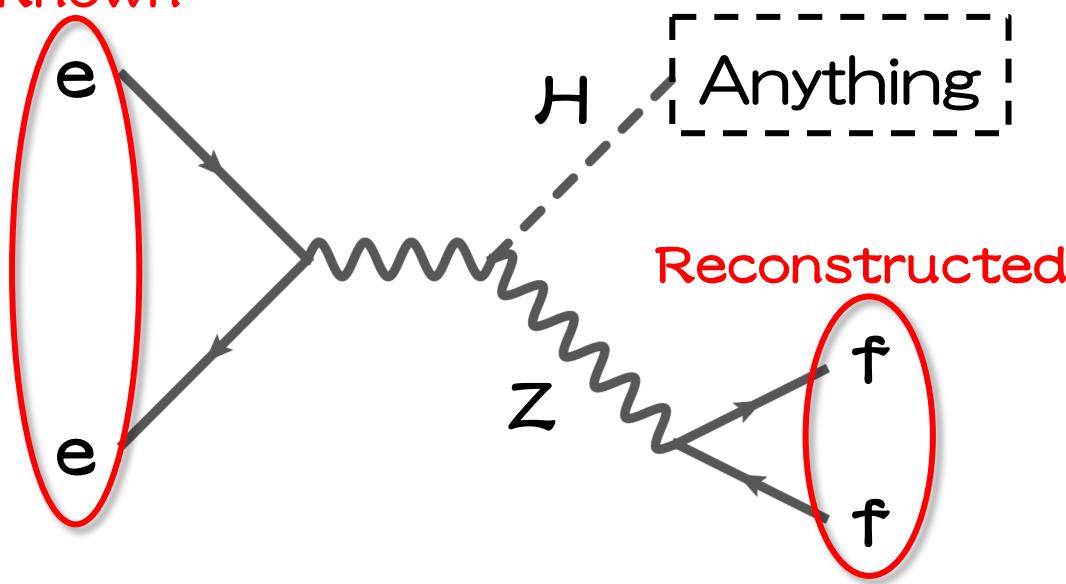
- Top quark precision measurement
- Colorless new particle search

➤ **Higgs high sensitive measurements**

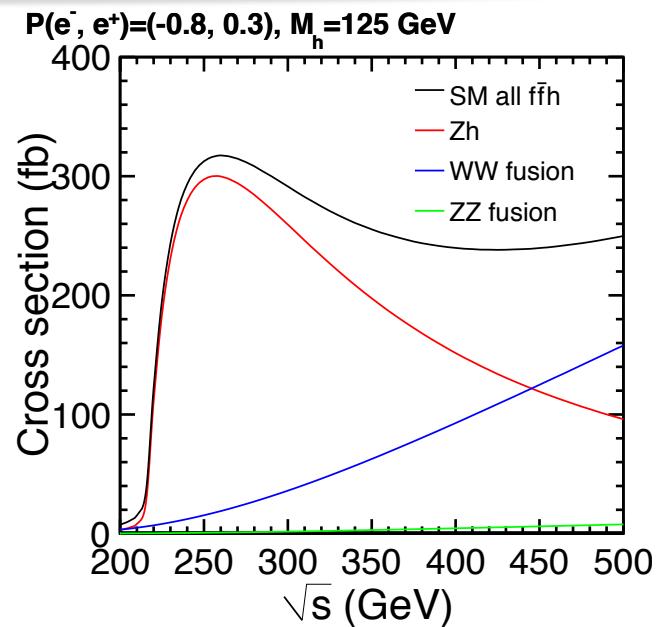
ILC as a Higgs factory

- $E_{CMS}=250\text{GeV}$ is tuned for Higgs measurements.
- $e^+e^- \rightarrow Zh$ is a golden mode.
- Recoil mass technique provides results independent on Higgs decay model.

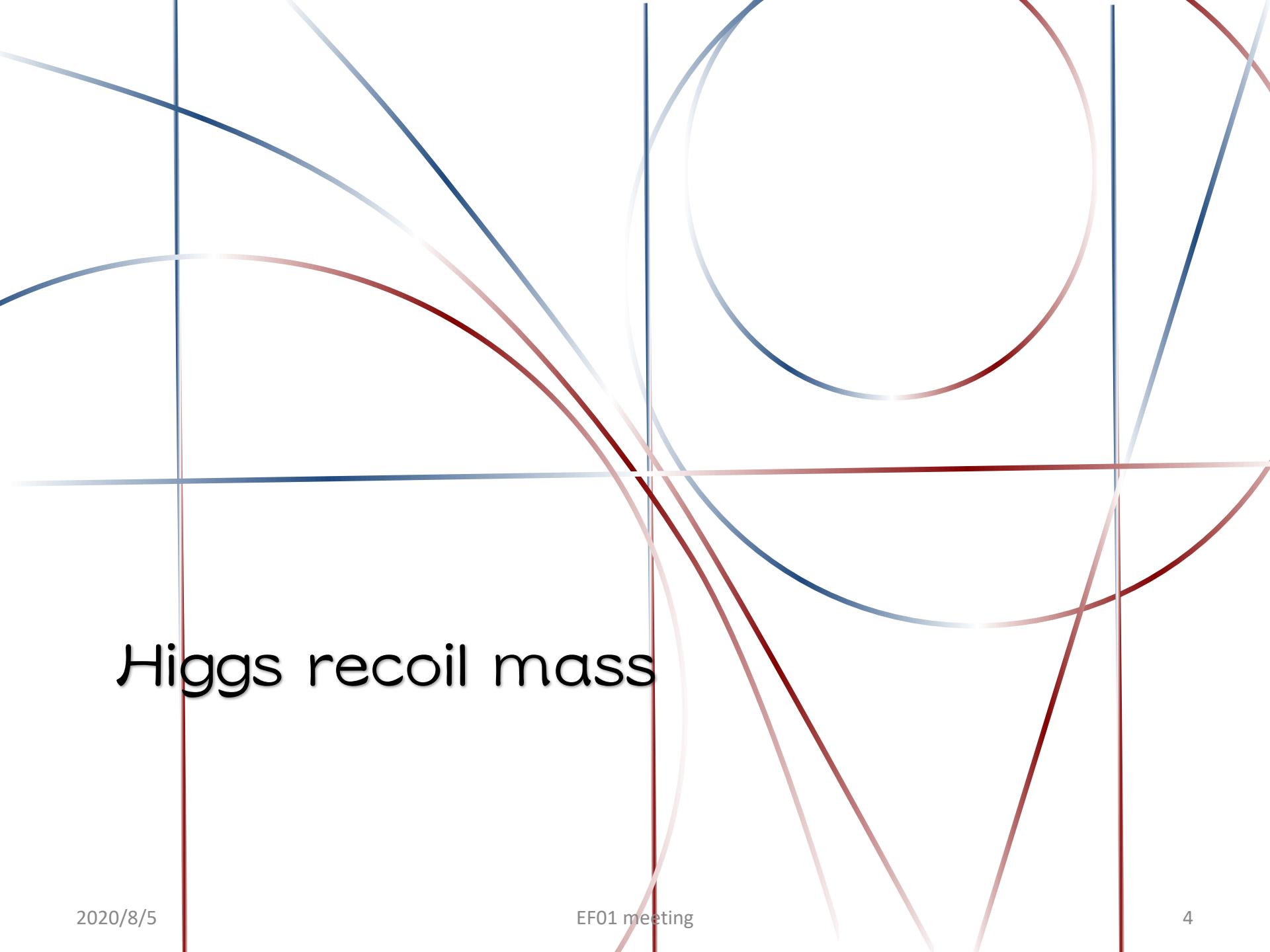
Known



$$M_{recoil} = (\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2$$



- High precision determination of Higgs mass.
- Measurement of absolute value of Zh cross section.
- $H \rightarrow$ invisible decay (DM) search.



Higgs recoil mass

Analytical setup

Higgs mass	Center of mass energy	Integrated Luminosity	Spin polarization
125 [GeV/c ²]	250 [GeV]	Scaled to 900fb ⁻¹ + 900 fb ⁻¹	P(e ⁻ , e ⁺) =(±0.8, ±0.3)

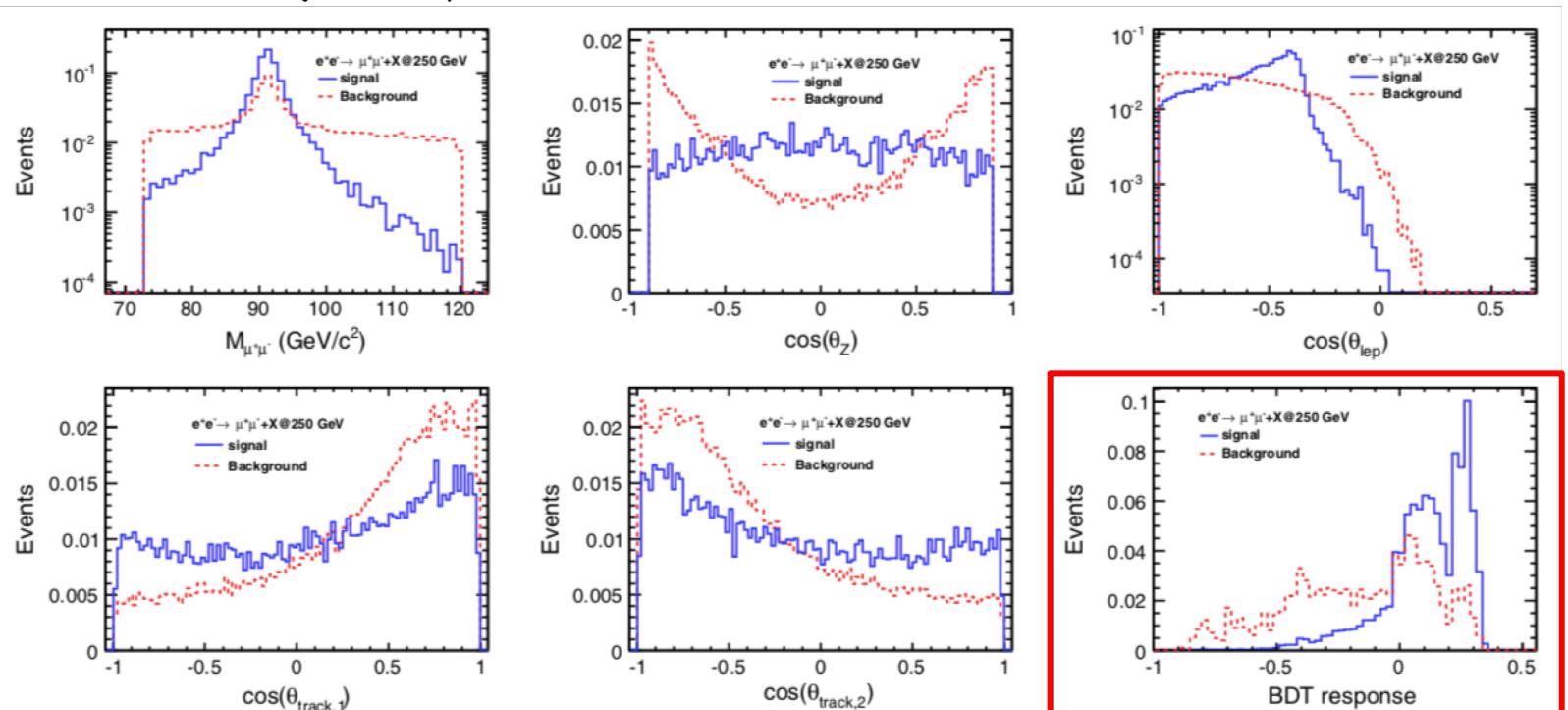
- Phys.Rev.D 94 (2016) 11, 113002
- $E_{CMS}=250\text{GeV}$ is peak of Zh cross section
- Compare different polarization scenario
 - Left handed (eLpR)
Larger signal cross section
 - Right handed (eRpL)
Suppressed BG come from W
- Statistical uncertainties are scaled with 900fb^{-1} for eLpR and 900fb^{-1} for eRpL.

BG suppression

- Main sources of BG are 2f, 4f_l, and 4f_sl.
- M_{l+l+} , $p_T(l+l+)$, $\cos\theta_{\text{missing}}$ and BDT cuts are adopted.
 - Signal efficiency is required to be independent on Higgs decay modes for the cross section measurement.
- For E_{visible} cut, categorizing $\sigma(\text{Zh})$ into $H \rightarrow \text{visible}$ and invisible parts is very useful.
 - $\sigma(\text{Zh}) = \sigma_{\text{vis}} + \sigma_{\text{inv}}$
 - $H \rightarrow \text{invisible}$ study is required.

Assumption of σ

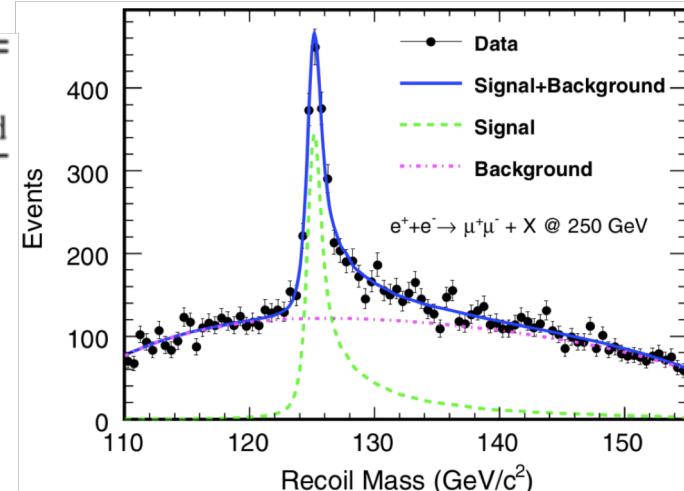
$\sqrt{s} = 250 \text{ GeV}$	cross section		N_{Gen}	
	polarization		left	right
		left	right	
$\mu^+\mu^-H$		10.4 fb	7.03 fb	17.1k 11.0k
e^+e^-H		10.9 fb	7.38 fb	17.6k 11.2k
2f_l		38.2 pb	35.0 pb	2.63M 2.13M
2f_h		78.1 pb	46.2 pb	1.75M 1.43M
4f_l		5.66 pb	1.47 pb	2.25M 0.35M
4f_sl		18.4 pb	2.06 pb	4.43M 0.36M
4f_h		16.8 pb	1.57 pb	2.50M 0.24M
total background		157.1 pb	86.3 pb	13.6M 4.51M



Sensitivity

Cut table

$\int \mathcal{L} dt = 250 \text{ fb}^{-1}$	$\mu^+ \mu^- H e_L^- e_R^+$	signal efficiency	signal significance	total background
no cut	2603	100%	0.42	1.98×10^7
Lepton ID + Precut	2439	93.70%	7.46	104344
$M_{l^+ l^-} \in [73, 120] \text{ GeV}$	2382	91.51%	8.09	84341
$p_T^{l^+ l^-} \in [10, 70] \text{ GeV}$	2335	89.70%	11.17	41322
$ \cos \theta_{\text{missing}} < 0.98$	2335	89.70%	12.71	31378
$\text{BDT} > -0.25$	2310	88.74%	15.03	21311
$M_{\text{rec}} \in [110, 155] \text{ GeV}$	2296	88.21%	16.37	17378
$E_{\text{vis}} > 10 \text{ GeV}$	2293	88.09%	20.94	9694



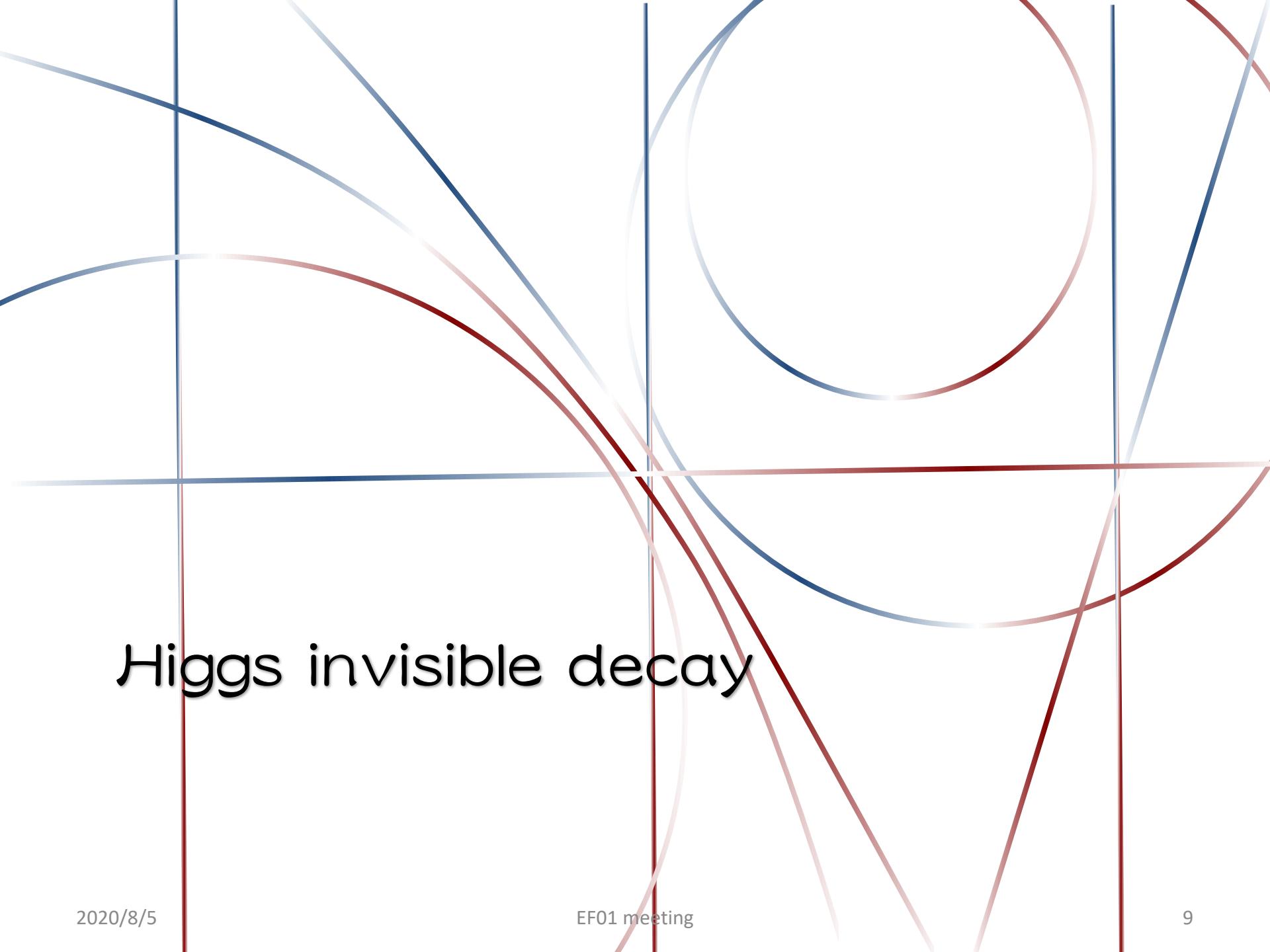
- σ_{vis} is measured here.
- M_{recoil} distribution is fitted by :
 - Kernel function (Signal)
 - Chebychev pol. (BG).
- $Z \rightarrow q\bar{q}$ channel can be also combined.
 - less clean, but larger statistics.
 - [arXiv:1903.01629](https://arxiv.org/abs/1903.01629)

250 GeV 900fb ⁻¹	eLpR		eRpL	
	$\sigma_{\text{vis}}(\text{Zh})$	Mass	$\sigma_{\text{vis}}(\text{Zh})$	Mass
$\mu\mu H$	1.7%	21 MeV	1.9%	23 MeV
eeH	2.1%	64 MeV	2.5%	79 MeV
Combined	<u>1.3%</u>	<u>20 MeV</u>	<u>1.5%</u>	<u>22 MeV</u>

- Combining eLpR and eRpL, $\Delta M_H = 14 \text{ MeV}$.
 - Combining $Z \rightarrow ll/q\bar{q}$,
- $\Delta \sigma_{\text{vis}} = 1.0\% \text{ (eLpR) and } 1.0\% \text{ (eRpL).}$

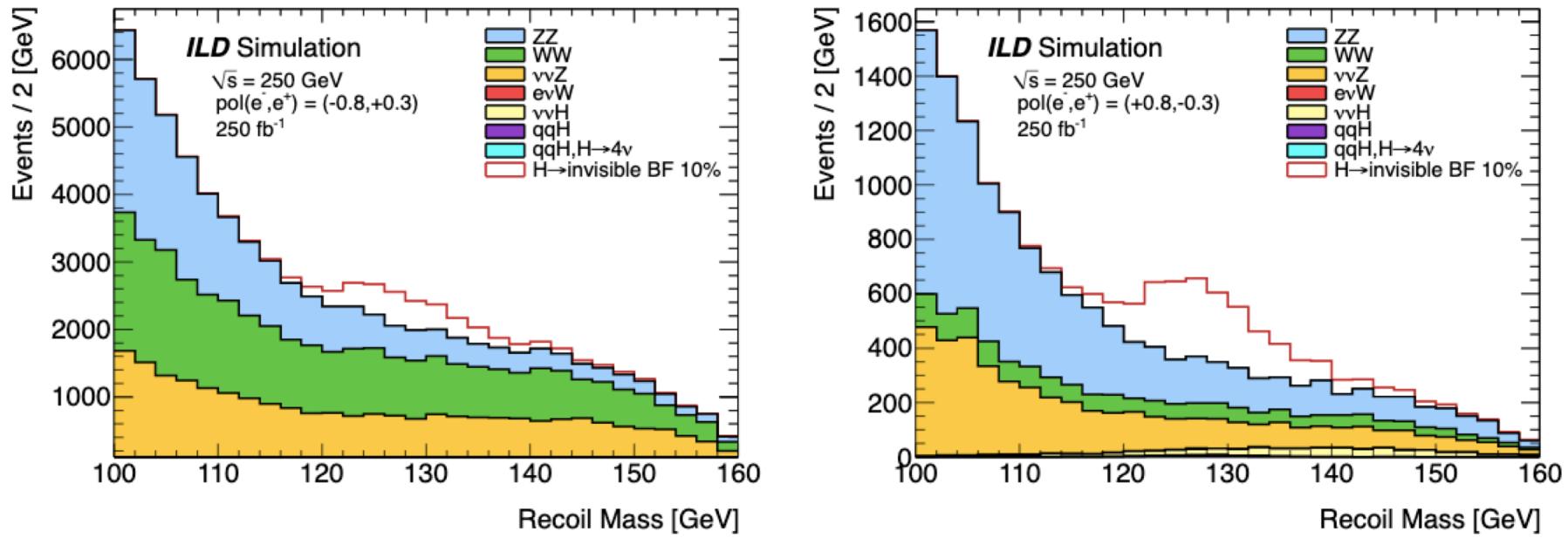
About systematic uncertainty

- This is an open question → Snowmass study very welcome
- A source of systematics is beam energy uncertainties
 - The uncertainty of the peak energy position (20-30 MeV).
 - The uncertainty of the beam energy spectrum (to be investigated).
 - New method of \sqrt{s} estimation with $e^+e^- \rightarrow \mu^+\mu^-$
→ μ momentum-scale will be calibrated using $J/\psi \rightarrow \mu^+\mu^-$
(snowmass EFO4, G.Wilson).
- The further study is required to estimate the uncertainties and their impacts on Higgs mass measurement.
- Another possibility is to introduce completely different methods, which have very complementary systematic errors:
 - Direct reconstruction method using Higgs decay
(PhD thesis, A.Ebrahimi)
 - Angular method using only transverse momentum balance
(ILD-PHY-2019-001, J.Tian)
 - ZH threshold scan method
(LCWS2017, G.Wilson)
 - Direct reconstruction in leptonic channels
(LCWS2017, G.Wilson)



Higgs invisible decay

H \rightarrow invisible



- [arXiv:1909.07537](https://arxiv.org/abs/1909.07537), [arXiv:2002.12048](https://arxiv.org/abs/2002.12048), and Junping's ALCW2015 talk
- The recoil mass technique provides good U.L. on $\text{BR}(H \rightarrow \text{invisible})$.
 - Key detector performance : Jet energy resolution
 - SM : $\sim 0.1\%$ for $H \rightarrow ZZ \rightarrow 4\nu$
 - Z \rightarrow qq channel provides the best contribution for its large statistics.
 - eRpL data is much better than eLpR for the suppressed BG.

- * eLpR/eRpL combined results
- * 350GeV can be also combined.

U.L. on BR (95% C.L.)	Z \rightarrow ll/qq
@250GeV 1.8ab^{-1}	0.23%
@500GeV 3.2ab^{-1}	0.65%
Combined	0.22%

Summary

- One of the most important feature of the ILC is Higgs factory.
 - Especially $e^+e^- \rightarrow Z h$ is a golden mode measured at $E_{\text{CMS}}=250\text{GeV}$.
 - The **recoil mass technique** provides highly sensitive measurements of mass and (absolute) cross section.
- The full detector simulation for ILD was performed.
 - $\Delta\sigma_{L/R} = 1.0\%$ ($Z \rightarrow qq/ll$) / $\Delta M_H = 14\text{MeV}$ ($eLpR+eRpL$).
 - The dominant systematic uncertainty study is needed.
- The recoil technique also gives $H \rightarrow \text{invisible}$ BR U.L.
 - Combining $Z \rightarrow qq/ll$ channels, $\text{BR} < 0.22\%$ (95% C.L.) is possible (1.8ab^{-1} @ 250GeV , 3.2ab^{-1} @ 500GeV).

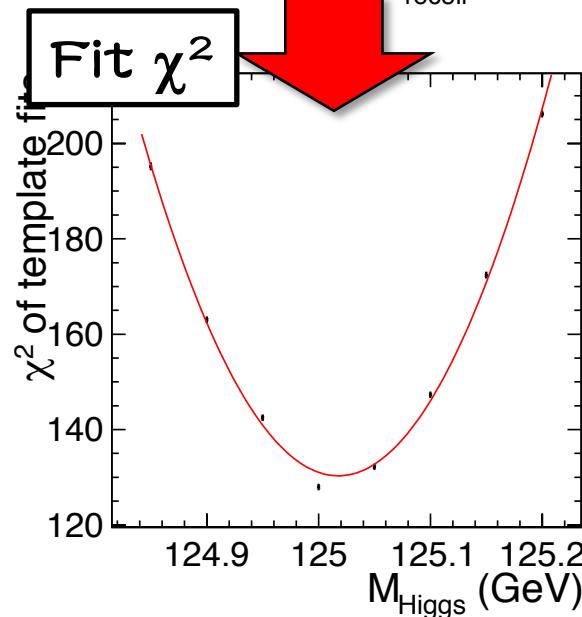
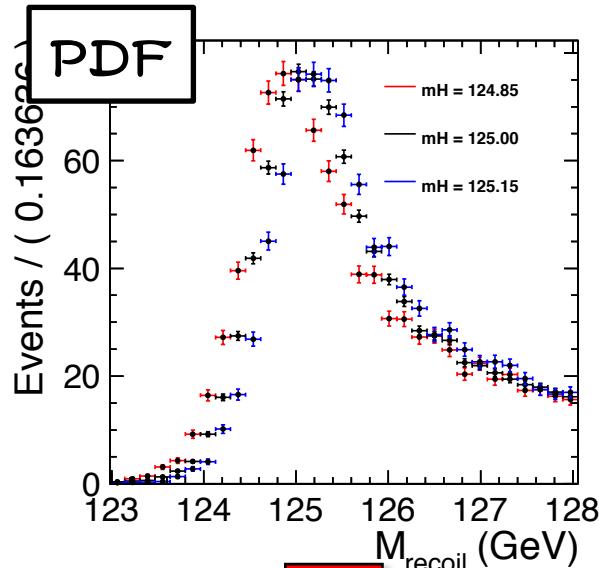
Backup

2020/8/5

EF01 meeting

12

Possible improvement



- To determine the Higgs mass, template method is expected to provide less systematics.
- Signal PDF prepared with slightly different mass assumptions.
 - 124.85, 124.90, 124.95, 125.00, 125.05, 125.10, ...
 - The minimum point of the χ^2 plot gives M_H information.

More information

- $H \rightarrow \text{invisible}$
@250, 350, 500GeV

Table 1: Integrated Luminosities with H-20 scenario.

E_{CM} [GeV]	“Left” [fb^{-1}]	“Right” [fb^{-1}]
250	1350	450
350	135	45
500	1600	1600

Table 3: Upper limits on the branching fraction of invisible decays of the Higgs boson in percent based on H-20 scenario.

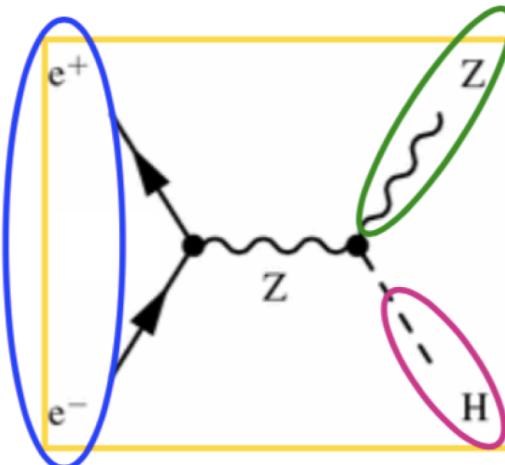
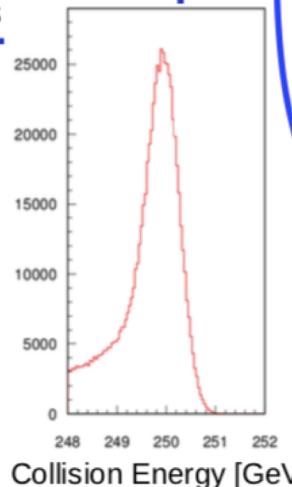
E_{CM} [GeV]	$Z \rightarrow q\bar{q}$			$Z \rightarrow q\bar{q}$ and $\ell^+\ell^-$		
	“Left”	“Right”	combined	“Left”	“Right”	combined
250	0.41	0.51	0.32	0.37	0.45	0.28
350	2.40	3.82	2.03	1.98	3.07	1.66
500	1.77	1.29	1.04	1.34	0.97	0.79
combined	–	–	0.30	–	–	0.26

- EFT framework requires to measure $\sigma(Zh)$ eLpR and eRpL separately (see [here](#)).

Higgs-strahlung

key to measurements independent of Higgs decay

initial 4-momentum
well-known
nominal CM energy
+ beam energy spread
[<0.2% / beam]
+ beamstrahlung
energy loss



4-momentum of Z
measured by
detector

→ infer recoiling system's 4-momentum

precision depends on:

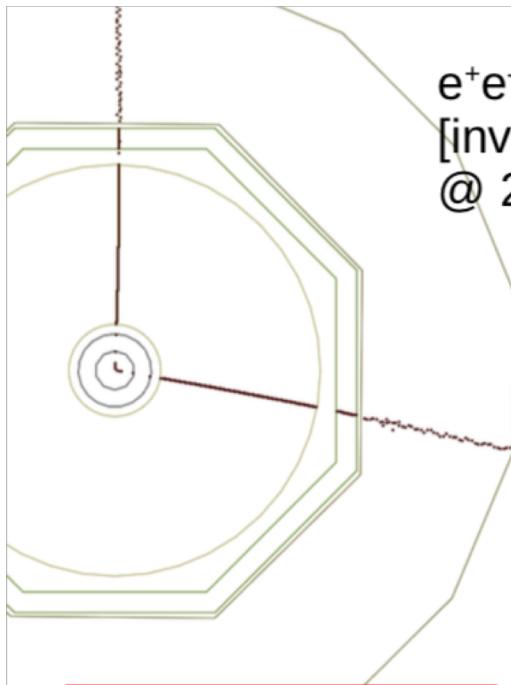
- collision energy spectrum
- Z measurement precision

defines required momentum resolution

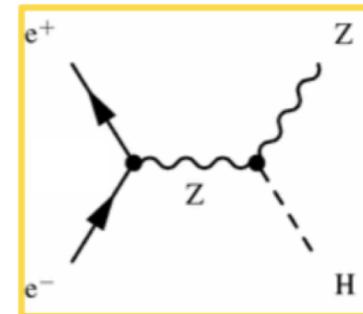
smearing due to Z momentum \sim smearing due to beam energy spread

$$dp_T/p_T \sim \text{few} \times 10^{-5} p_T \text{ @ high momentum}$$

8



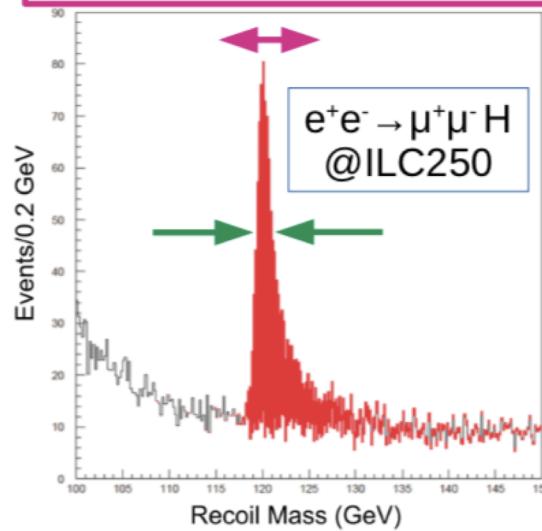
$e^+e^- \rightarrow \mu^+\mu^- h$
[invisible h decay]
@ 250 GeV



peak position:
Higgs mass ~ 14 MeV

peak area :
total $e^+e^- \rightarrow Z H$
cross-section
→ independent of
H decay

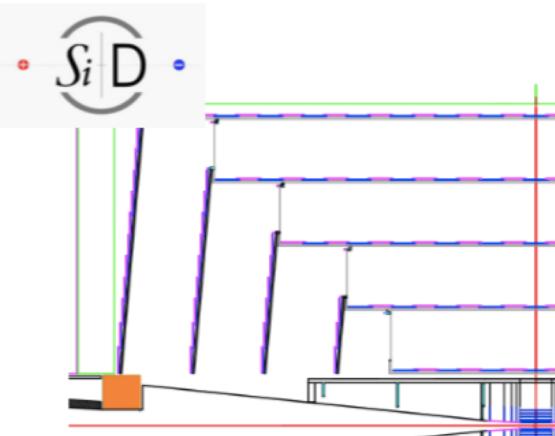
→ HZZ coupling
strength $\sim 0.4\%$



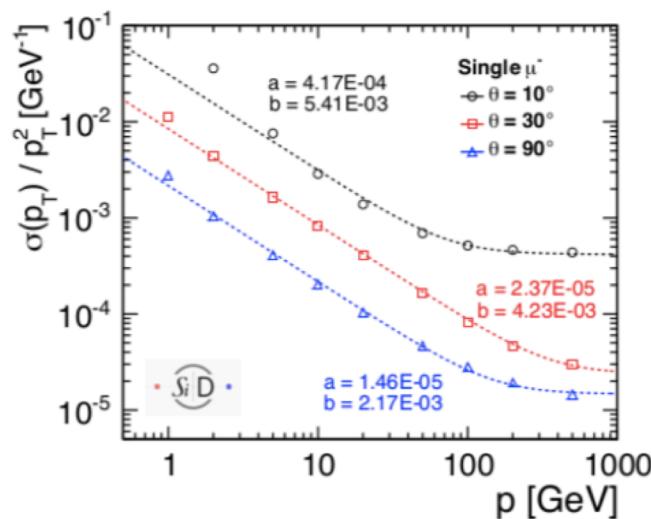
peak width:
→ drives precision

momentum resolution
⊕
beam energy spread

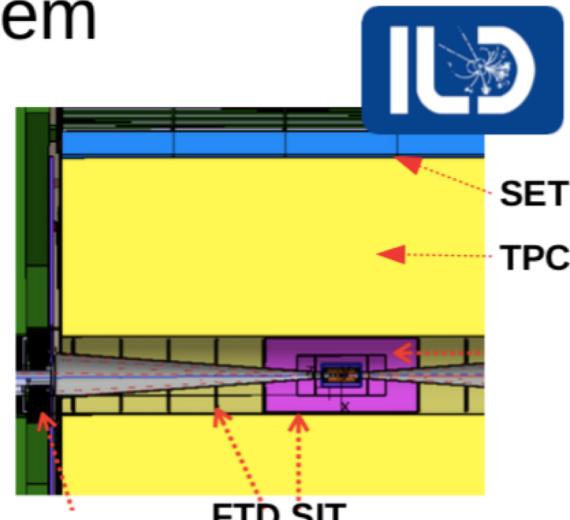
main tracking system



all-silicon tracking system
5 layers of strip sensors



contrasting approaches



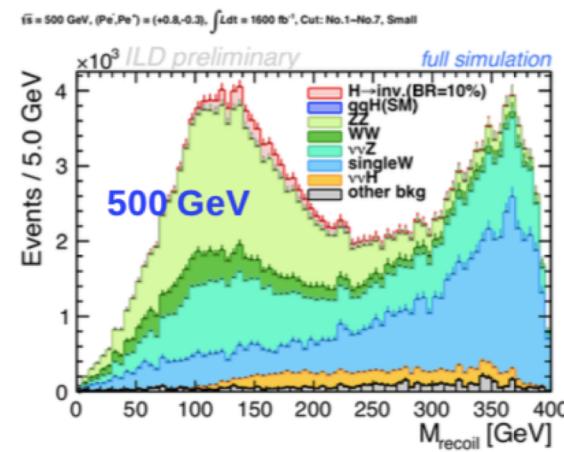
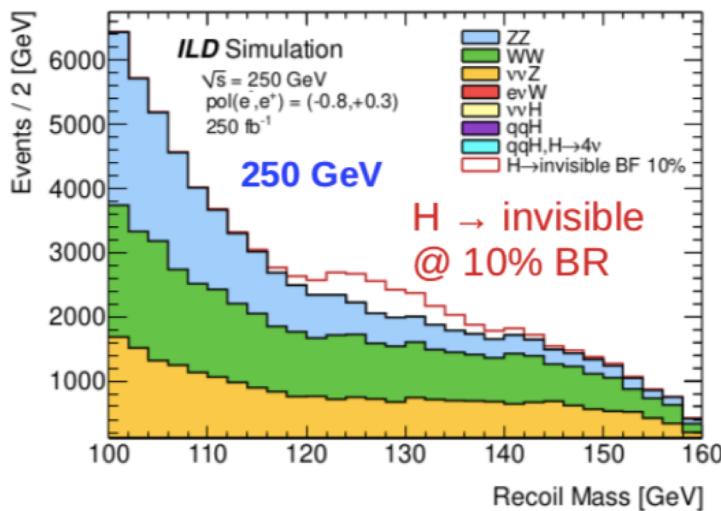
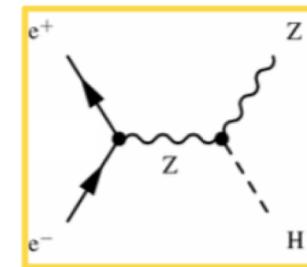
hybrid tracking system
Time Projection Chamber (TPC)
+ silicon (SET, SIT, FTD)

both achieve
required
performance

10

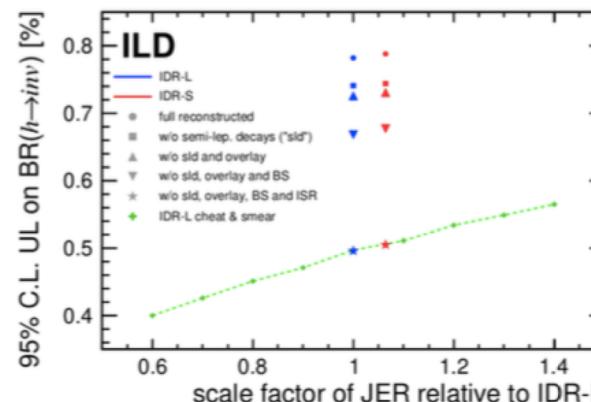
Higgs decay to invisible final states e.g. dark matter particles?

hadronic Z decays for maximum sensitivity



limit on additional invisible
Higgs decay BR: ~0.3%

arXiv:1909.07537, 2003.01116
ILD-PHYS-PUB-2019-003



17